Parton propagation and energy loss at an EIC

Alberto Accardi

Hampton U. and Jefferson Lab

POETIC 7

Temple U., 14 November 2016

With many thanks to M.Baker, W.Brooks, V.Morozov, I.Vitev for help preparing this talk

Outline

- **Broad picture:**
  - Parton propagation and hadronizationin nuclear matter
  - What have we learned so far?
  - The EIC: a unique opportunity to understand in-medium QCD dynamics

- **Deeper discussion, news:**
  - [Tue 1B] Ivan Vitev – eA jets
  - [Tue 2B] Felix Ringer – ep jets
    Yulia Furletova – nuclear gluons
  - [Wed 4B] Elke Aschenauer – pp, pA and EIC
  - [Wed 5B] Bin Wu – pT-broadening
  - [Wed 6B] Abhijt Majumder - nTMDs

Parton propagation and hadronization

Open questions in QCD

- **What role do sea quarks and gluons play in nucleon structure?**
  - Spin, angular momentum

- **What are the properties of fundamental QCD nuclear color fields?**
  - Shadowing, gluon saturation, universal "gluonic matter"

- **How does colored radiation:**
  - **interact with QCD matter?**
  - **materialize into colorless hadrons?**
  - Parton and hadron propagation in the nuclear medium
  - Parton energy loss, shower development, reaction of the medium

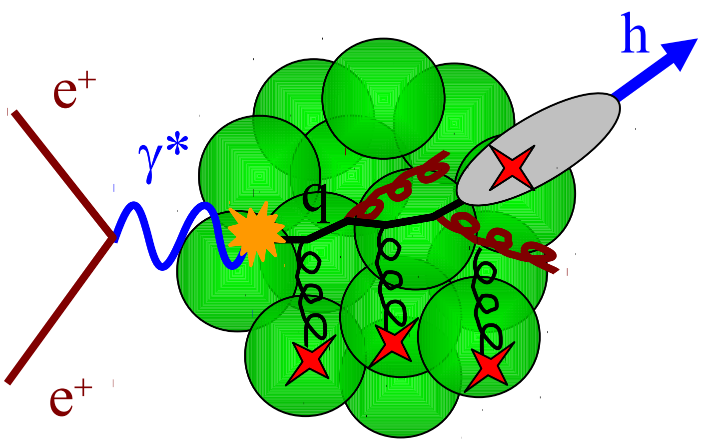
Accardi et al., Eur.Phys.J. A48 (2012) 92
"Nuclear physics with a medium–energy EIC"

EIC white paper, Eur.Phys.J. A52 (2016) 268
"Electron Ion Collider: The Next QCD Frontier"

Parton propagation and hadronization

Review: Accardi et al., Riv. Nuovo Cim. 032,2010

- **Nuclei as space-time analyzers**



Transverse momentum broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

Hadron attenuation

$$R_M = (N^h/N^e)_A/(N^h/N^e)_D$$

Small ν ⇒ hadronization inside

Large ν ⇒ hadron boosted outside, quark propagation in nuclei

Parton propagation and fragmentation

Review: Accardi et al., Riv. Nuovo Cim. 032,2010

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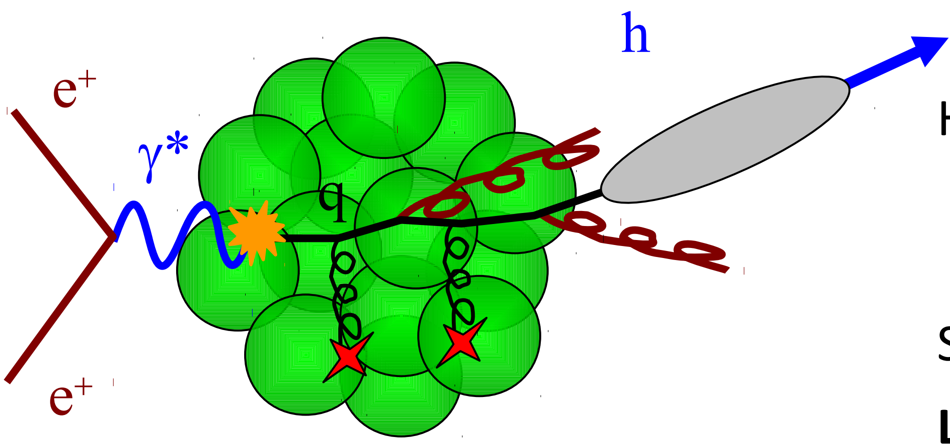

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- **Non perturbative aspects**
  - Color confinement dynamics
  - Probe soft nuclear gluons
- **Perturbative QCD**
  - Testing pQCD energy loss
  - Parton shower mechanism
  - Coupling to nuclear medium

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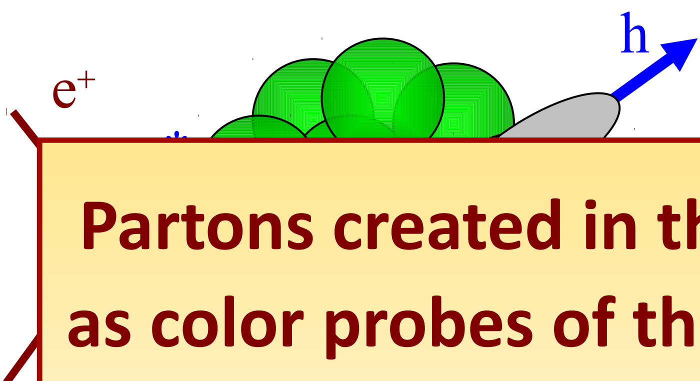


Transverse momentum broadening

$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

Hadron attenuation

$N^e)_D$

le

tside,

in nuclei

Partons created in the medium can be used as color probes of the nuclear medium when <u>parton lifetime</u> and <u>energy loss mechanisms</u> are under theoretical control

- **Non perturbative aspects**
  - Color confinement dynamics
  - Probe <u>soft</u> nuclear gluons

- **Perturbative QCD**
  - Testing pQCD energy loss
  - Parton shower mechanism
  - Coupling to nuclear medium

Towards Nuclear Chromo Dynamics

- **Experimental access to nuclear gluon fields**
  - Quarks couple to soft (small-x) gluons
  - Attenuation, pT-broadening, induced gluon radiation governed by **"transport coefficients" → accessible experimentally**
  - **Related to fundamental properties of gluonic matter** (hot & cold)

- **Transport coefficients ⟷ Gluon field correlators**

$$
\left.
\begin{aligned}
\hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^-\left\langle U^\dagger F^{a+i}(y^-)UF_i^{a+}(0)\right\rangle \\
\hat{e} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^-\left\langle iU^\dagger \partial^- A^{a+}(y^-)UA^{a+}(0)\right\rangle \\
\kappa &= \frac{4\pi\alpha_s}{3N_c}\int d\tau\left\langle U^\dagger F^{a0i}(\tau)t^a UF^{b0i}(0)t^b\right\rangle
\end{aligned}
\right\} \text{Momentum / energy diffusion}
$$

Majumder, Mueller

Towards Nuclear Chromo Dynamics

- **Experimental access to nuclear gluon fields**
  - Quarks couple to soft (small-x) gluons
  - Attenuation, pT-broadening, induced gluon radiation governed by **"transport coefficients" → accessible experimentally**
  - **Related to fundamental properties of gluonic matter**

- **E.g., access to gluon saturation scale**
  - In dipole model

Maximal gluon density

$$\Delta p_T^2 \approx 2T_A(b) \left. \frac{d\sigma_{q\bar{q}}^N(r_T)}{dr_T^2} \right|_{r_T=\frac{1}{Q_{sat}}} \approx Q_{sat}^2$$

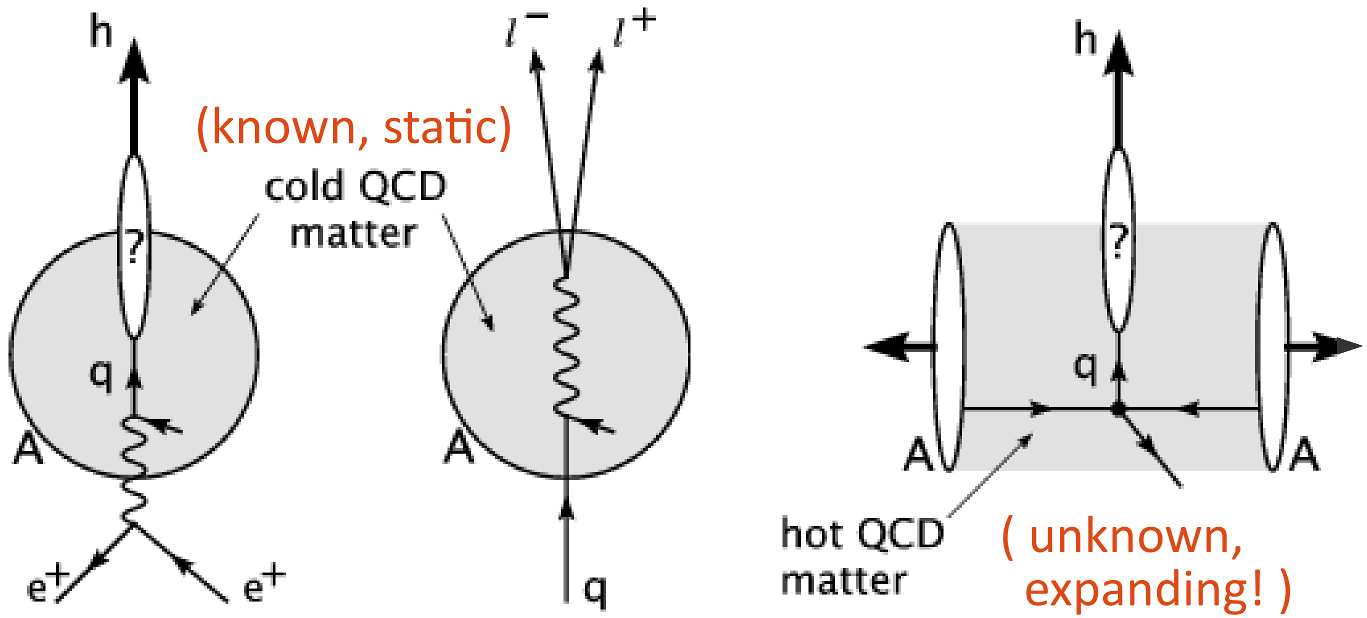
Multiple soft scatterings

IR cutoff

Kopeliovich et al., PRC81 (2010) 035204

Cold and hot nuclear matter

Review: Accardi et al., Riv. Nuovo Cim. 032,2010



DIS
FS energy loss
+ hadronization

DY
IS energy loss
+ nuclear PDFs

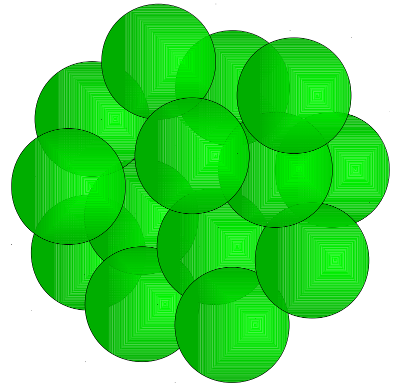
properties of the QGP

DY vs. e+A
antishadowing

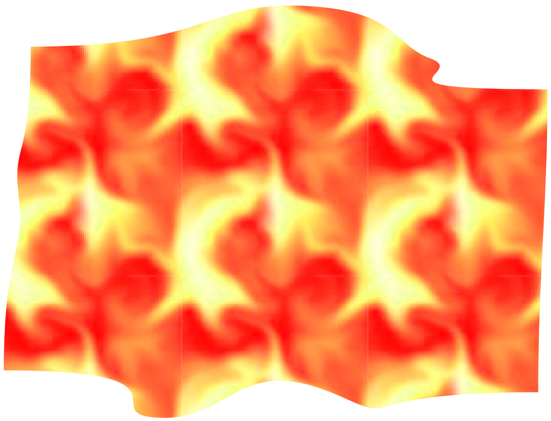
Bricks, Nuclei, and the QGP

The Brick

Armesto et al., PRC 86 (2012) 064904



The nucleus



The QGP

The JET collaboration, PRC 90 (2014) 014909

Cold nuclei as experimental benchmark for analytic and MC implementations of QCD energy loss:

– known density, known d.o.f., static
– nucleons as femto-detectors
– e-loss, parton showers, time scales

Bricks, Nuclei, and the QGP

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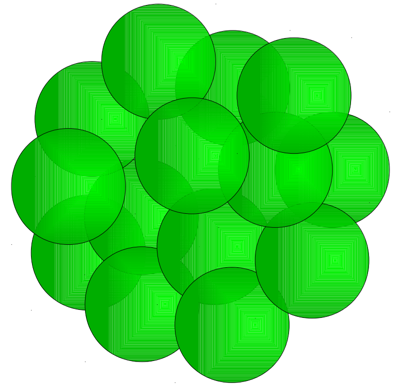
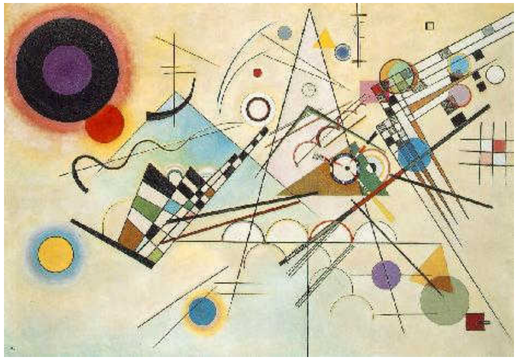
Armesto et al.,
PRC 86 (2012) 064904



The nucleus



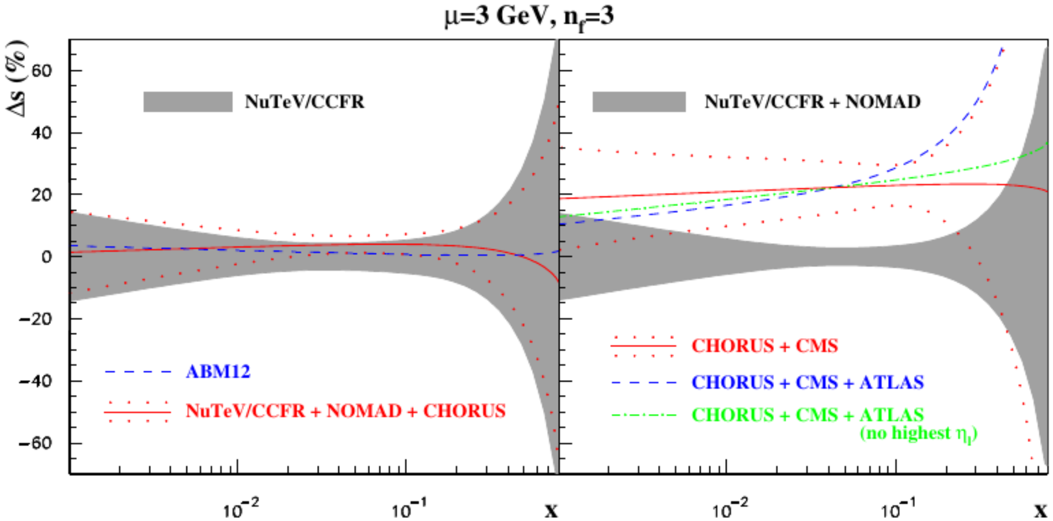
The QGP

The JET collaboration,
PRC 90 (2014) 014909

Cold nuclei are necessary to reveal the true nature of the QGP!

Strange, strange quarks

- **ν+*A* → dimuons** *vs.* ***p+p* → *W+c* at LHC** *Alekhin et al., arXiv:1404.6469*

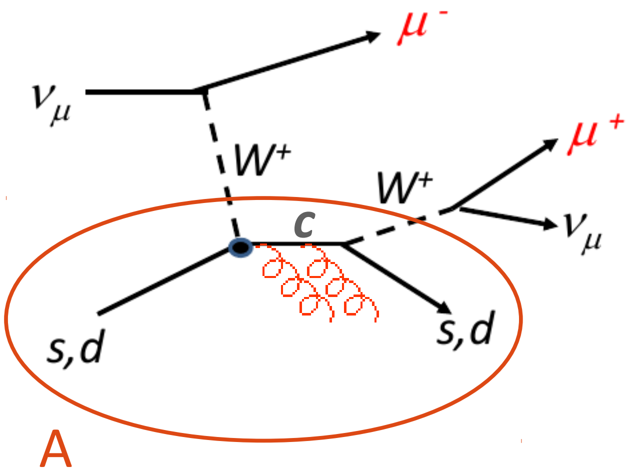


$$g\, s_p \to W\, c$$

$$\nu\, s_A \to \mu^- \mu^+ \nu_\mu\, s$$

FSI ?

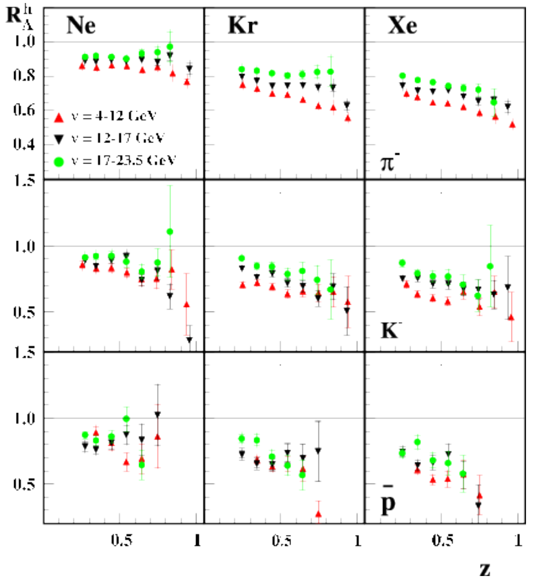
- **<u>Final state propagation of *c* quark / D meson</u>**
  - Not quite under theoretical or phenomenological control, yet (*cf.* heavy quark "puzzle" in A+A at RHIC, LHC)



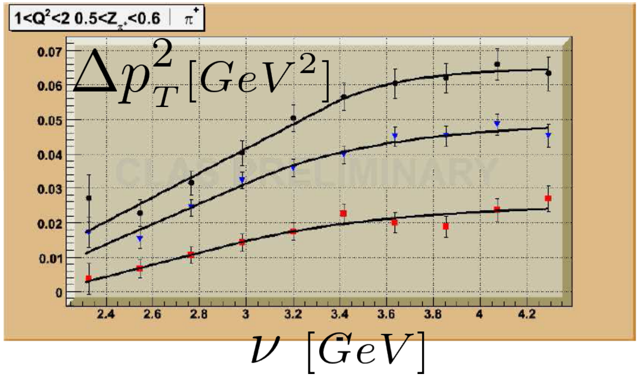
What have we learned so far?

Hadronization at HERMES and JLab

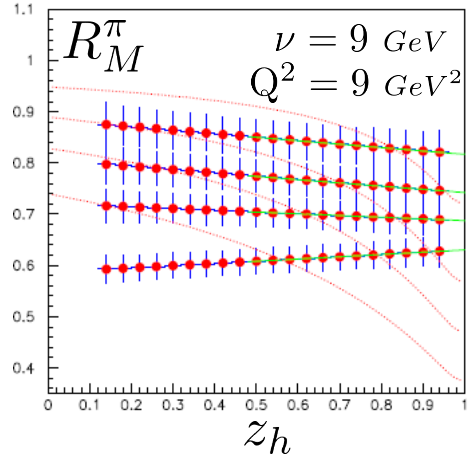
- **HERMES:**
  - First precise flavor separation (π,K,p)
  - 2D distributions



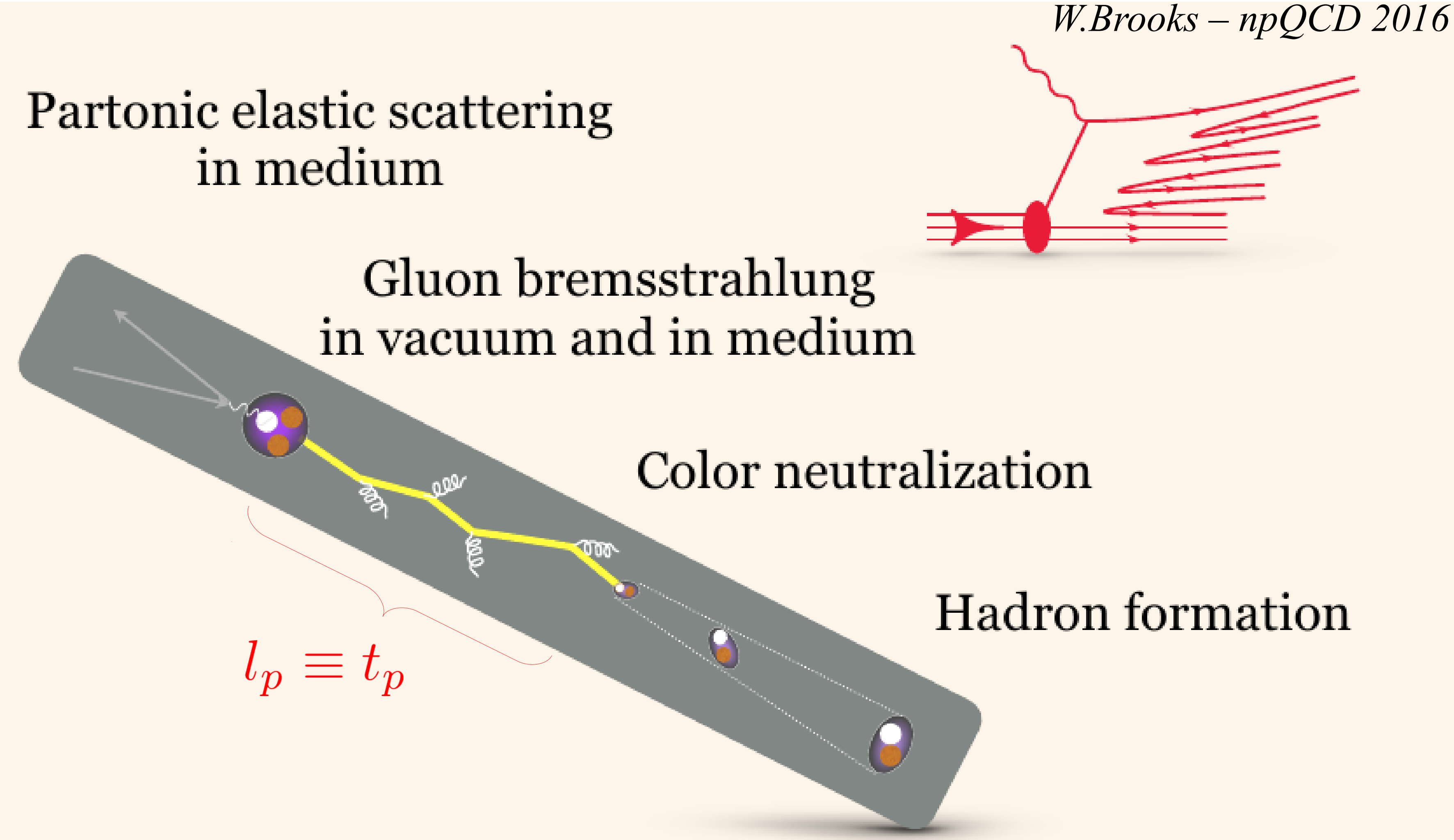
- **JLab 6:**
  - Preliminary 3D pions
  - first η , K_0 ever



- **JLab 12 – E12-06-117:**
  - Up to 5D distributions
    (z, x, ν, p_T, θ)
  - Multiple flavors
  - More leverage in ν, Q^2

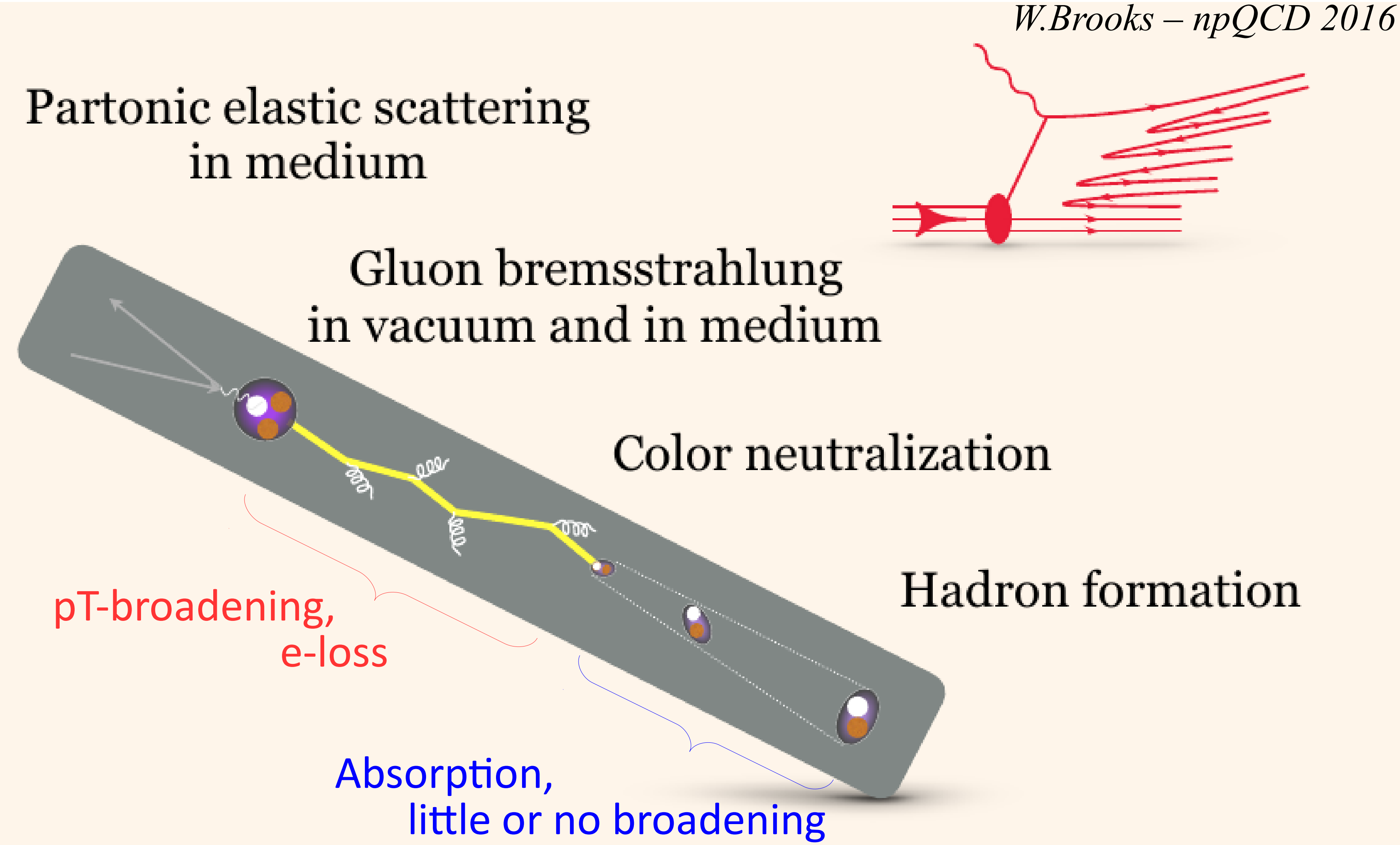


Basic time scales



We implant this process in large nuclei and compare to deuterium

Basic time scales

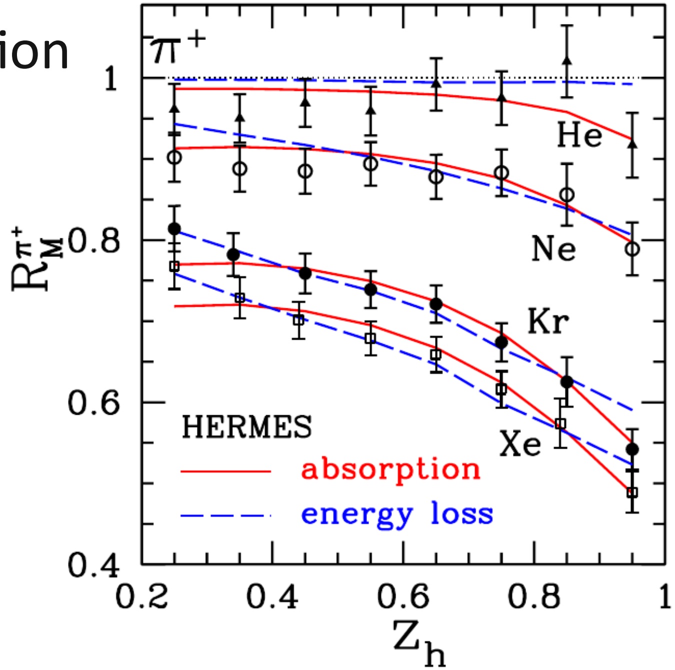


We implant this process in large nuclei and compare to deuterium

Absorption or energy loss?

- Both pure absorption (short lp) and pure en.loss (large lp) reproduce hadron attenuation
  - No control over time scales
- If long-lived quarks, can extract $\hat{q}$
  - But large uncertainties from different e-loss implementations
  - Non-negligible "MC" effects

Accardi et al.
Riv. Nuovo Cim. 032, 2010



- For example:
  - Analytic quenching-weights + realistic geometry (blue lines in fig.)

$$\hat{q} \approx 0.6\ \mathrm{GeV}^2/\mathrm{fm}$$

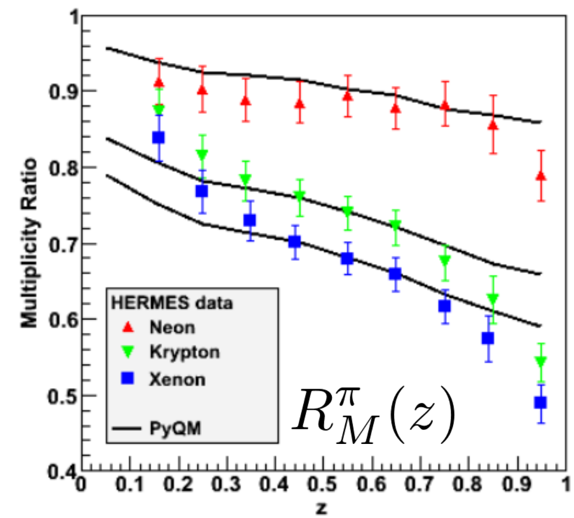
  - PyQM: same as above, but as Pythia afterburner :

$$\hat{q} \approx 0.4\ \mathrm{GeV}^2/\mathrm{fm}$$

Accardi, Dupre
Dupre, Ph.D. thesis 2011

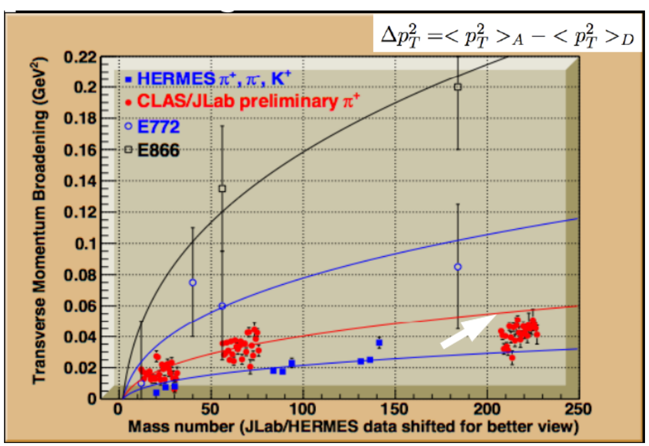
Absorption or energy loss?

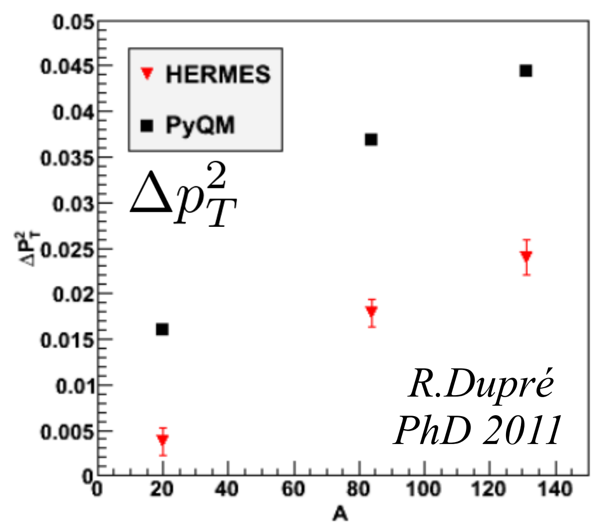
- Minimally, need to consider **both** attenuation and pt-broadening:
  - Depends on 2 transport coefficient
  - **Strong constraints on models**



- HERMES: linear in A → long quark lifetime

- CLAS: lower energy → shorter lifetime
  - Saturation of pT broadening
  - **Color neutralization inside the nucleus?**

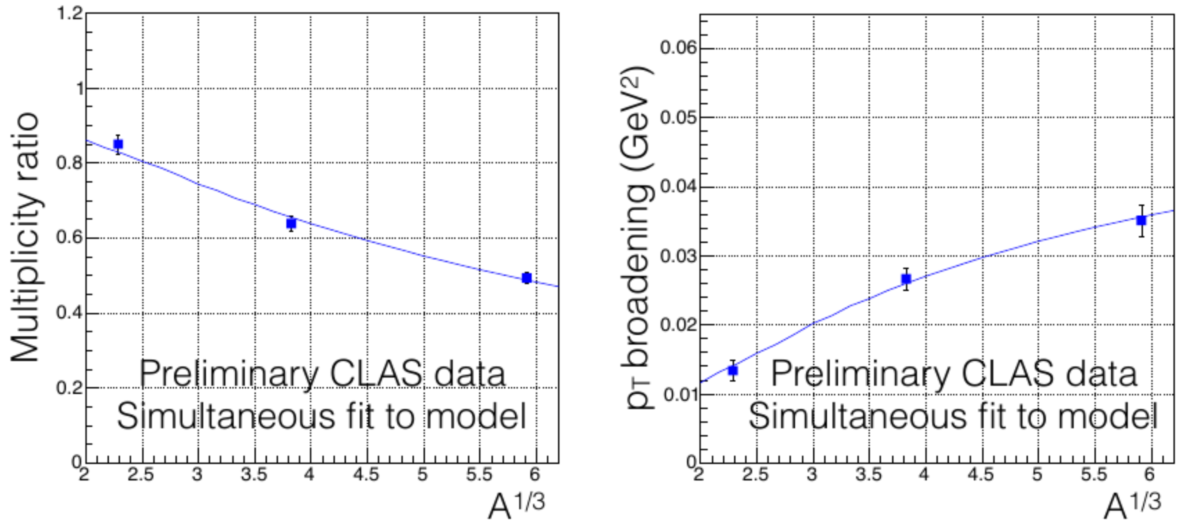




Basic time scales: absorption or energy loss?

- "Geometric model" analysis of CLAS data: *Brooks et al., npQCD 2016*
  - pT broadening from quark pahse only
  - Hadron attenuation from prehadronic phase on

Example of fit (one of 150 bins in x, Q^2, and z)



$\langle x \rangle=0.166$, $\langle Q^2 \rangle=1.17\ GeV^2$, ($\langle \nu \rangle=3.76$ GeV), $\langle z \rangle=0.445$

$L_p=1.8\pm0.4$ fm

$\chi^2/dof = 0.5$

Simultaneous fit *couples* p_T broadening to multiplicity ratio

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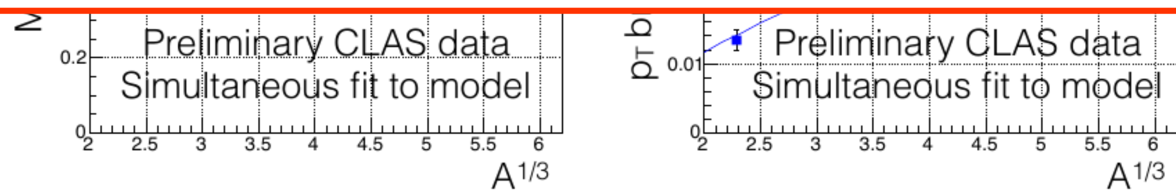
Example of fit (one of 150 bins in x, Q^2, and z)

in pion production:

$$L_p/\gamma = 0.88 + 0.18^*Q^2 - 0.16^*\nu \equiv f(\nu,Q^2)$$

(Parameter uncertainties 10-20%, chisquared/dof ~0.5)



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Simultaneous fit *couples* p_T broadening to multiplicity ratio

Near future: CLAS12

Brooks et al., npQCD 2016

- A bit larger energy, longer production times; expanded PID

DIS channels: *stable* hadrons, accessible with 11 GeV

JLab future experiment PR12-06-117

Actively underway with existing 5 GeV data

HERMES

meson	cτ	mass	flavor content	baryon	cτ	mass	flavor content
π^0	25 nm	0.13	ud	p	stable	0.94	ud
π^+, π^-	7.8 m	0.14	ud	$\bar{p}$	stable	0.94	ud
η	170 pm	0.55	uds	Λ	79 mm	1.1	uds
ω	23 fm	0.78	uds	Λ(1520)	13 fm	1.5	uds
η'	0.98 pm	0.96	uds	Σ^+	24 mm	1.2	us
φ	44 fm	1	uds	Σ^-	44 mm	1.2	ds
f1	8 fm	1.3	uds	Σ^0	22 pm	1.2	uds
K^0	27 mm	0.5	ds	Ξ^0	87 mm	1.3	us
K^+, K^-	3.7 m	0.49	us	Ξ^-	49 mm	1.3	ds

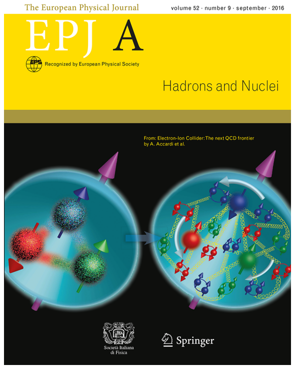
Enters the EIC

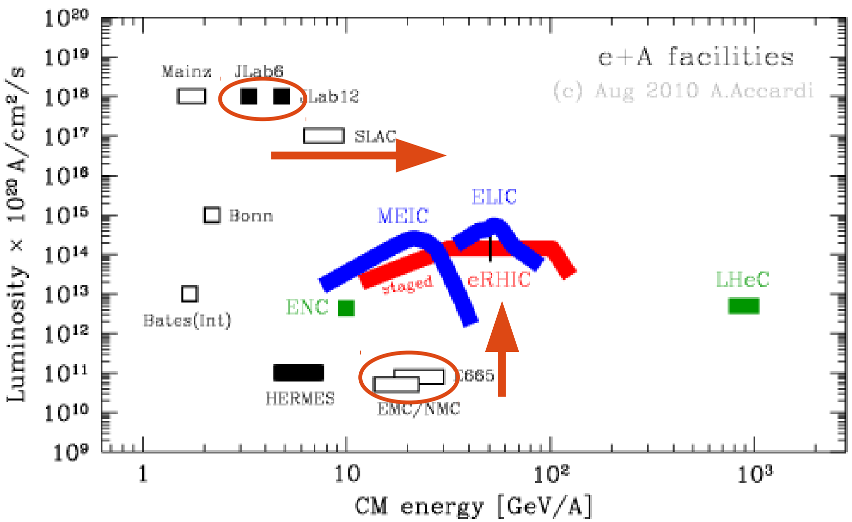
The future: the Electron-Ion Collider

- ❑ **High luminosity → precision studies**
- ❑ **Larger energy → unique opportunities**
  - **Very large ν, Q^2 leverage**
    - Hadrons in and out of medium
    - Deep perturbative regime
  - **Heavy quarks**
    - B and D, J/Ψ
  - **Jets in e+A**
    - In-medium parton showers
    - (almost) first time ever

Accardi et al., EPJA 48 (2012) 92

EIC white paper EPJA 52 (2016) 268





Quark life time (extrapolated from CLAS/HERMES)

Brooks et al., npQCD 2016

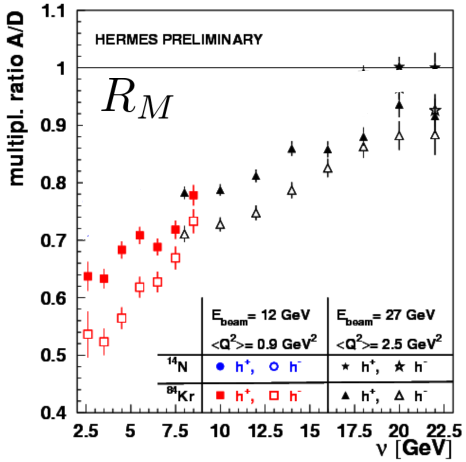
Using the prescription $\gamma = \nu/Q$ and $\beta = p_{\gamma^*}/\nu$, we can extrapolate:

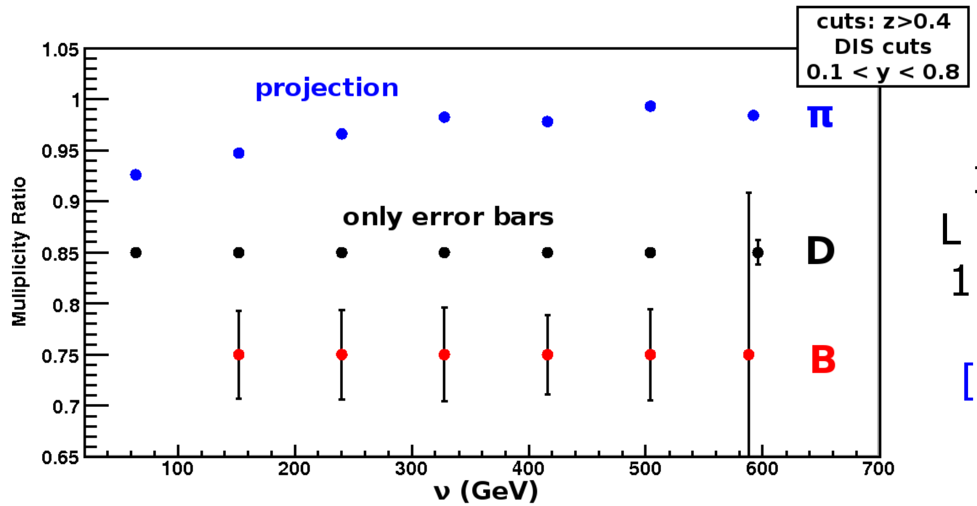
Q2	nu	beta*gamma	lp, z=0.32	lp, z=0.53	lp, z=0.75	lp, z=0.94	Experiment	x
2.40	14.50	9.31	8.57				HERMES	0.09
2.40	13.10	8.40		6.39			HERMES	0.10
2.40	12.40	7.94			4.63		HERMES	0.10
2.30	10.80	7.05				2.40	HERMES	0.11
3.00	4.00	2.08	1.92	1.58	1.21	0.71	CLAS	0.40
7.00	7.00	2.45	2.26	1.86	1.43	0.83	CLAS12	0.53
1.00	4.00	3.87	3.57	2.95	2.26	1.32	CLAS	0.13
2.00	9.00	6.28	5.79	4.78	3.66	2.14	CLAS12	0.12
12.00	32.50	9.33	8.59	7.10	5.44	3.18	EIC	0.20
8.00	37.50	13.22	12.17	10.06	7.71	4.50	EIC	0.11
45.00	140.00	20.85	19.20	15.86	12.15	7.10	EIC	0.17
27.00	150.00	28.85	26.57	21.96	16.82	9.82	EIC	0.10

At EIC we can study a wide range of production lengths!

(This is for pions; quarks shorter lived in heavier meson production)

Isolate, study energy loss





11+30 GeV/A Fe

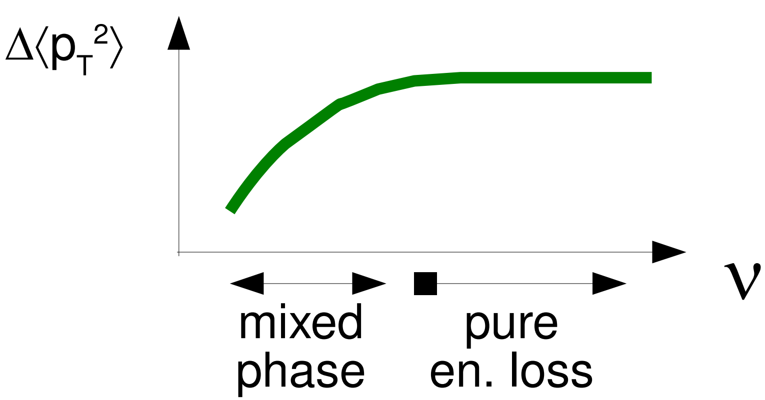
L = 0.4x10^{33} cm^{-2}s^{-1}

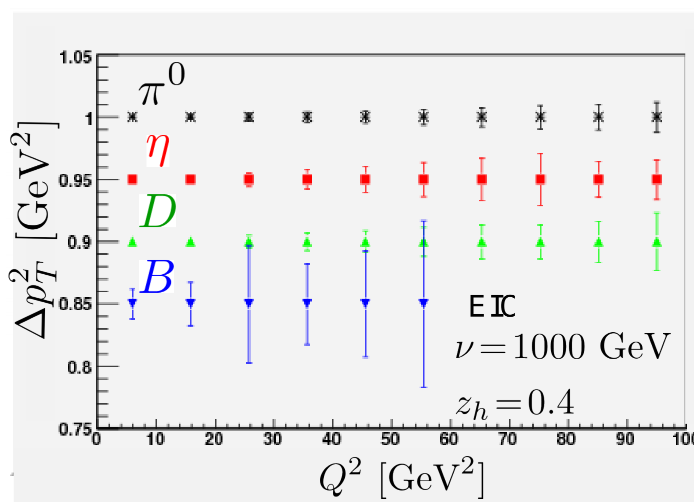
1 month, 100% eff.

[Dupré, Accardi]

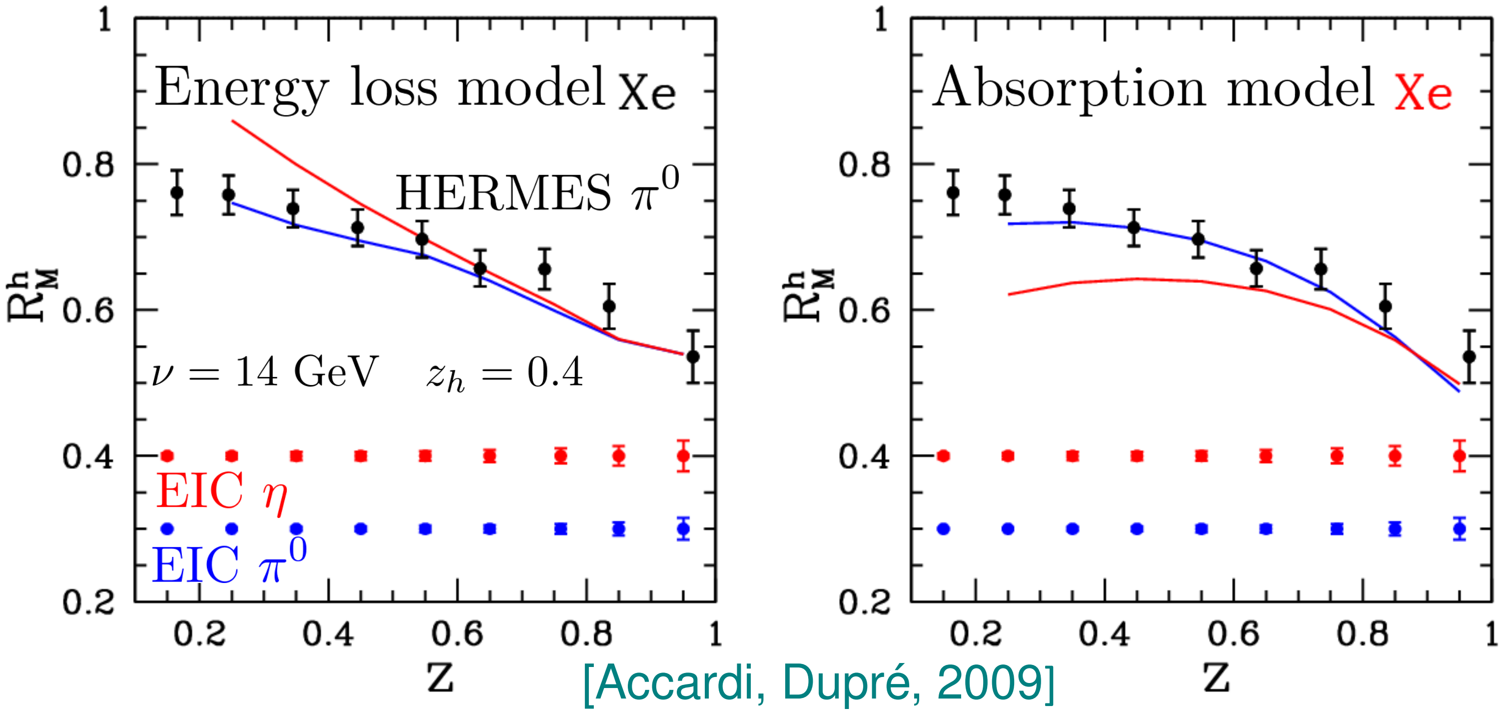
mixed phase

pure energy loss (?)





Exploit PID: hadronization mechanism

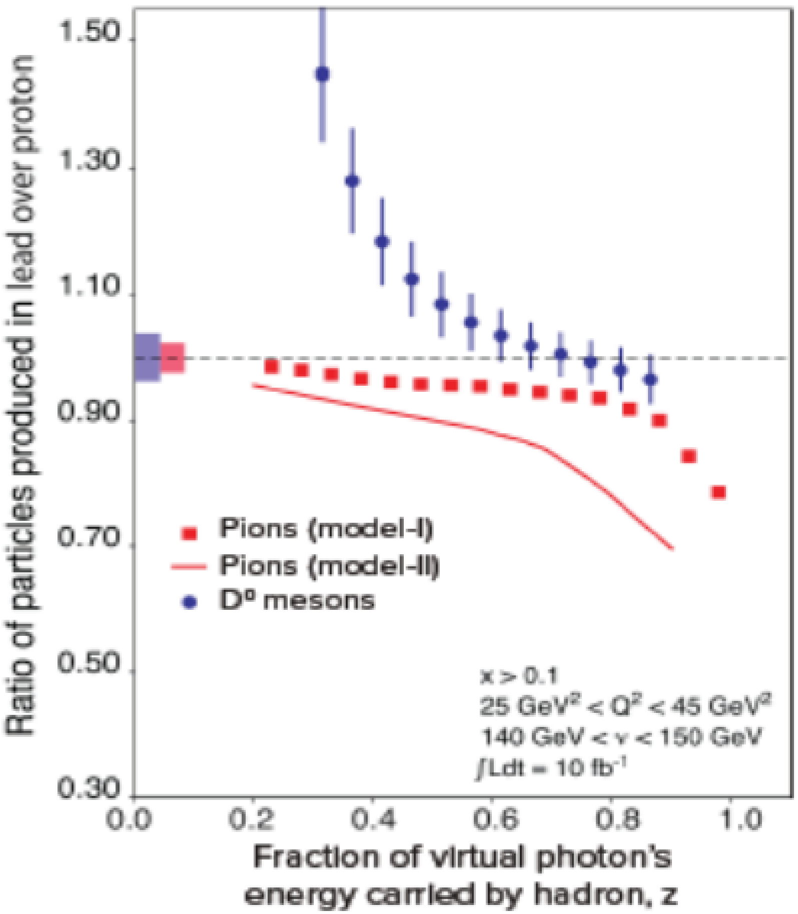


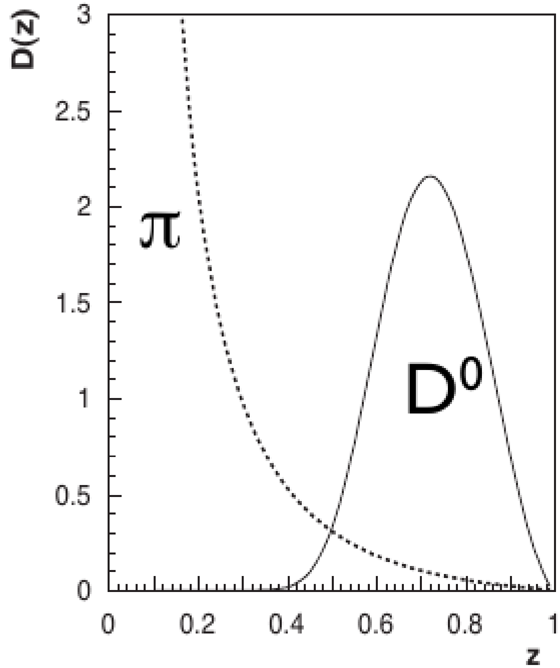
[Accardi, Dupré, 2009]

- Energy loss effects depend on shape of vacuum Frag. Function:
  - EIC can also measure these!

Exploit PID: heavy vs. light

- Dramatic difference in π vs. D^0 en.loss



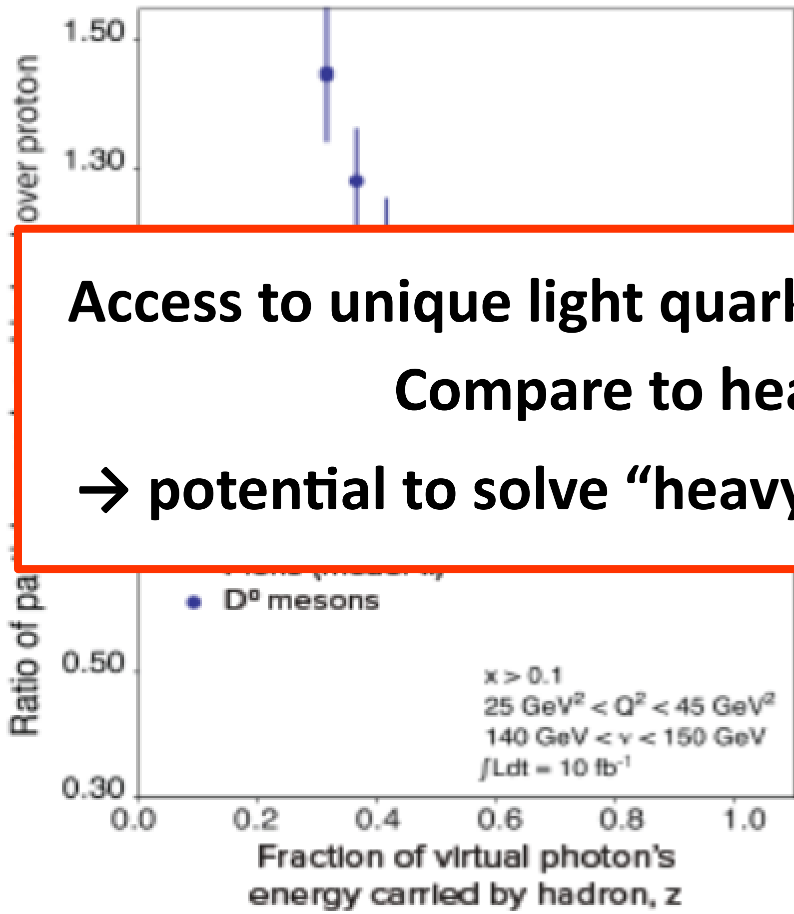


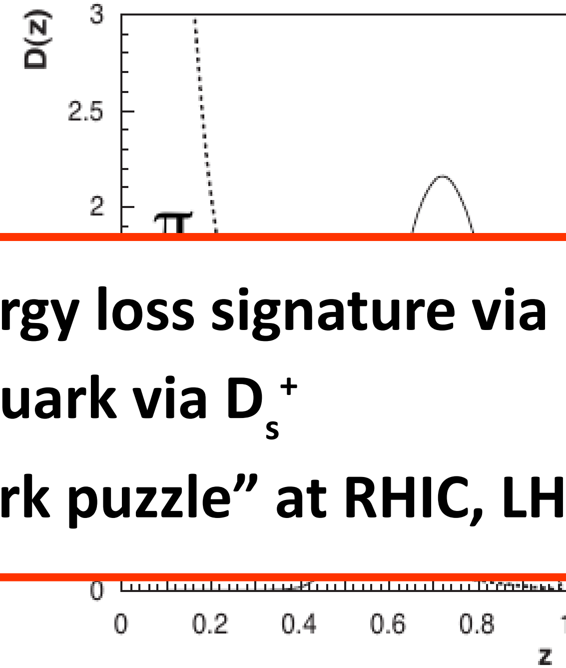
But: D0 <u>more</u> suppressed if produced inside the medium:

- More handles on time scales

Exploit PID: heavy vs. light

- Dramatic difference in π vs. D^0 en.loss





Access to unique light quark energy loss signature via D^0

Compare to heavy quark via D_s^+

→ potential to solve "heavy quark puzzle" at RHIC, LHC

But: D0 <u>more</u> suppressed if produced inside the medium:

- More handles on time scales

Towards Nuclear Chromo Dynamics

- DIS: known and static medium density
  - Propagating partons couple to soft color field (small-x gluons)
  - Energy loss, propagation governed by **"transport coefficients"**
  - **Fundamental gluon field correlators**

B. Mueller, talk at Confinement X, 2012

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle U^\dagger F^{a+i}(y^-) U F_i^{a+}(0)\right\rangle \\
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\kappa &= \frac{4\pi\alpha_s}{3N_c}\int d\tau \left\langle U^\dagger F^{a0i}(\tau) t^a U F^{b0i}(0) t^b\right\rangle
\end{aligned}\right\}$$

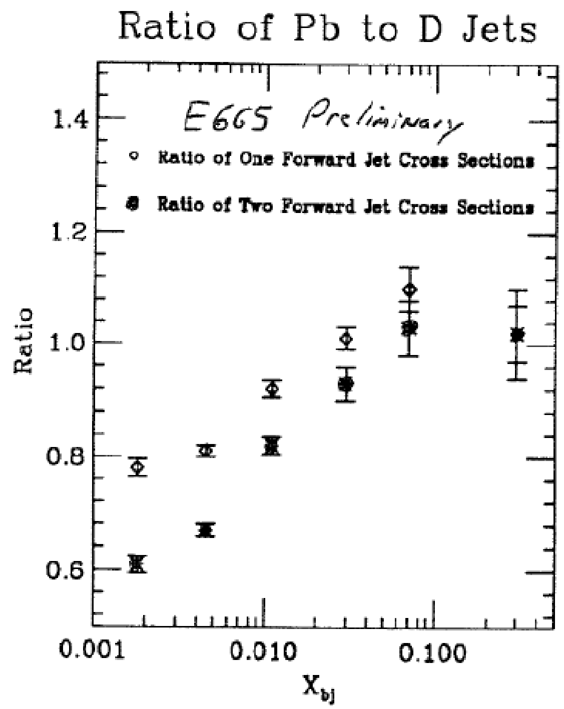
Momentum / energy diffusion

Nuclear physics in terms of fundamental d.o.f. !

Jets: a unique EIC opportunity

- **Features**
  - "Direct" access to parton energy loss (no Fragmentation Functions)
  - Plenty of infrared safe pQCD observables ("real" pQCD !)
  - Heavy quark tagging possible

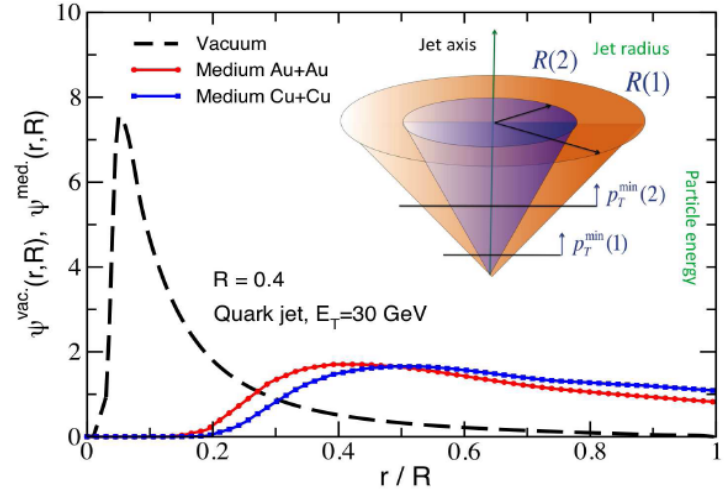
- **E665: proof of principle in e+A**
  - Jets can be measured in e+A at $\sqrt{s}$ > 30 GeV
  - results unpublished



- **RHIC & LHC: jets in A+A**
  - Used as probe for Quark-Gluon Plasma tomography
  - But: probe not calibrated (!)

Jets: a unique EIC opportunity

[I.Vitev]



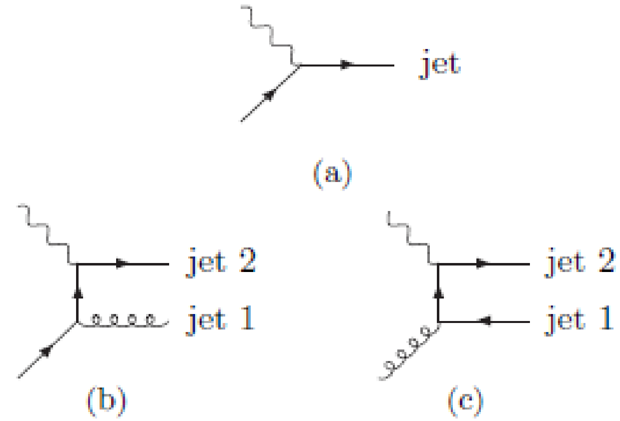
- **More handles on energy loss**
  - *e.g.*, jet rates vs. cone:
    (gluon radiation broadens the jets)
- **20 years of theory to be harvested**
  - Precise definitions of jets
    - IR and collinear safe
    - several algorithms, known advantages and disadvantages
  - Large choice of "jet shapes"
    - Characterization of energy flows inside the jet
    - Detailed parton shower algorithms in vacuum

Jets: a unique EIC opportunity

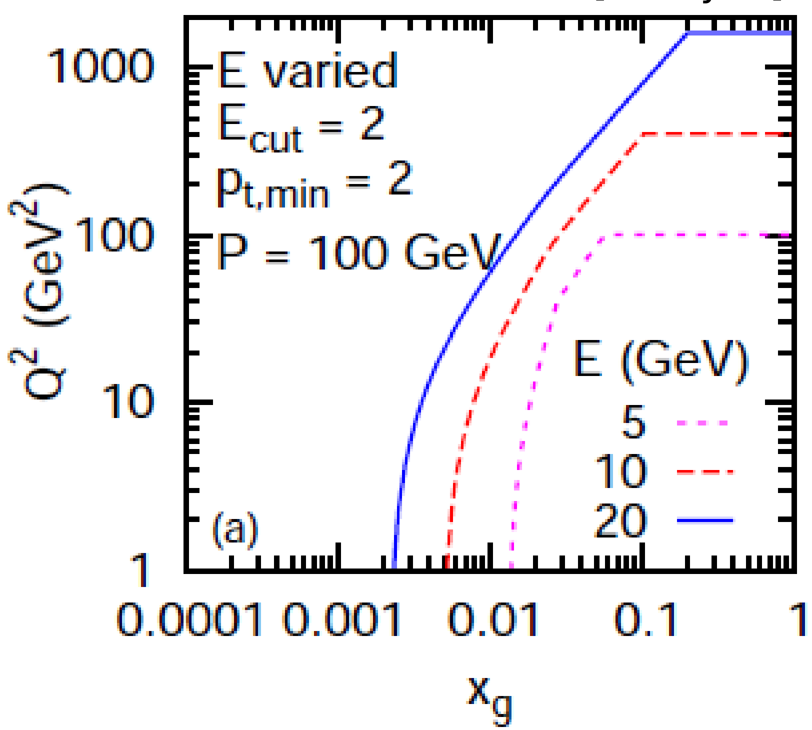
- **Dijets: alternative access to nuclear gluons**

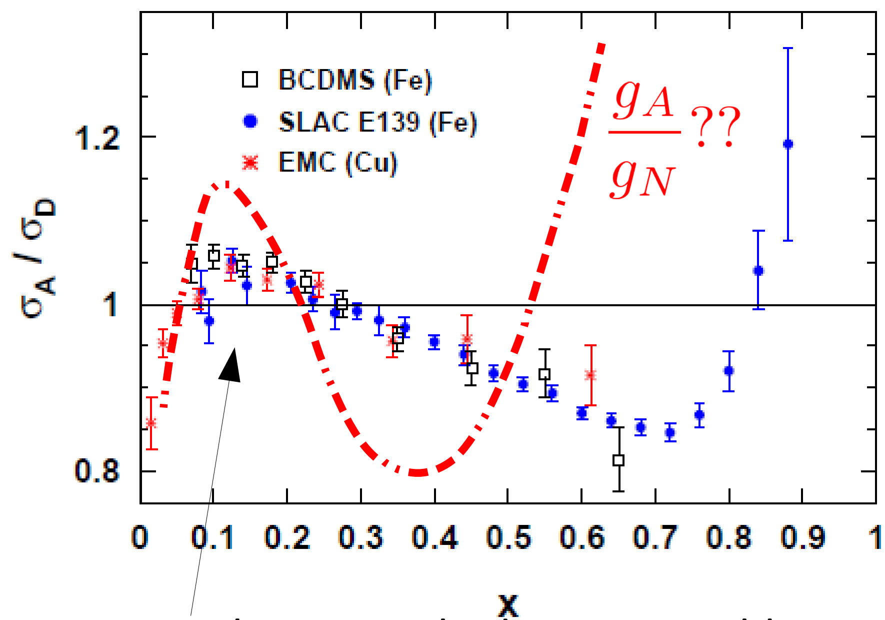
  → *Furletova [Tue 2B]: using charm quarks*

  - Pre-saturation region
  - Gluon antishadowing / EMC effect?



[G.Soyez]





Strong gluon anti-shadowing possible

Guzey et al., PRC 2012

Jets - new developments

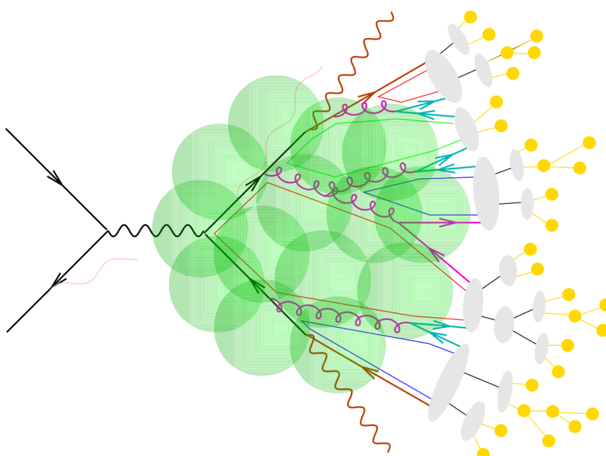
- **Soft Collinear Effective Theories**
  - Separation of hard and soft scales
  - SCETG: `[Idilbi,Majumder ; Ovanesyan,Vitev]`
    - Propagation of hard probe in a color charge background field
    - Medium-induced splitting functions

    $\rightarrow$ *Vitev [Tue 1B]*

    $\rightarrow$ *Ringer [Wed 4B]*
  - Factorization, resummation of event shapes
    - 1-jettiness `[Kang et al., 2013]`

Jets - parton showers

- **Calibration of the probe:**
  first (and only?) direct test of parton shower evolution
  - Essential element of MC generators (no Higgs spotting without!)
  - pQCD inspired, refined modeling, only indirectly tested
    - k_T vs. angular ordering
    - Many implementations, approximations (Pythia, Herwig, …)
    - …
  - Nuclei as space-time analyzers of the parton shower development



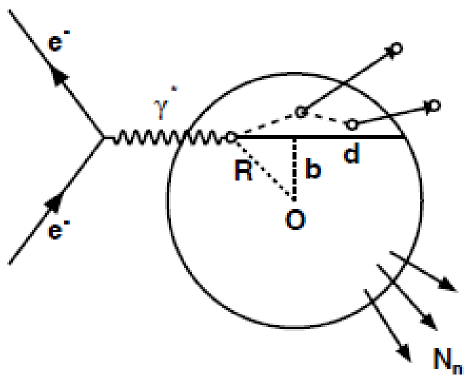
The eA energy loss generator desert

- **Plenty of MC generators in A+A**
  - Q-Pythia, CU-jets, JEWEL, HT parton shower
  - In principle, can be (easily?) extended to e+A !

- **Need e+A energy loss Monte Carlo simulations NOW !**
  - **PyQM** [Dupre, Accardi] : Pythia + quenching weights
    - First attempt, notable differences with analytic calculations
  - Implemented in **BeAGLE** [Aschenauer, Baker, Lee, Zheng]
    - To be tested within the Jlab "Geometry Tagging" LDRD

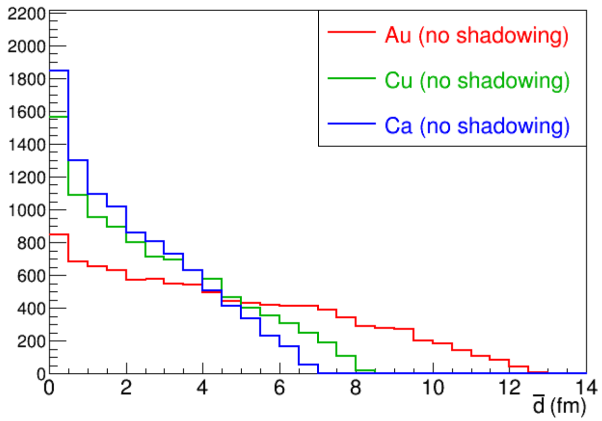
Jlab 2017-LDRD-6: Geometry tagging for heavy ions

A. Accardi, M. Baker, W. Brooks, R. Dupre, K. Hafidi, C. Hyde,
V. Morozov (co-PI), P. Nadel-Turonski (PI), K. Park, T. Toll, L. Zheng.

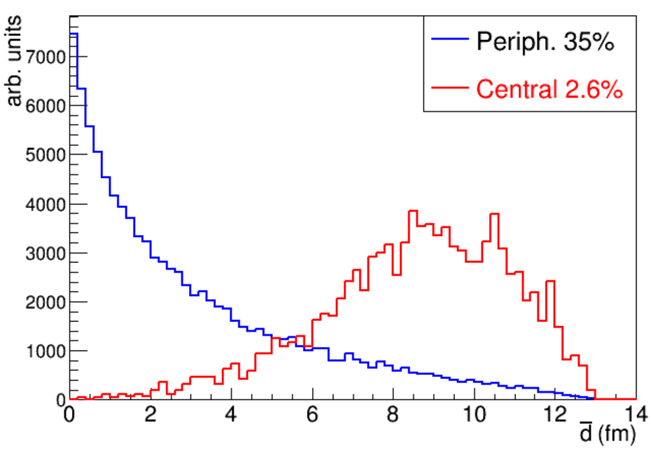


Intra-nuclear cascading increases with d (forward particle production)

Also evaporation of nucleons from excited nucleus (very forward)



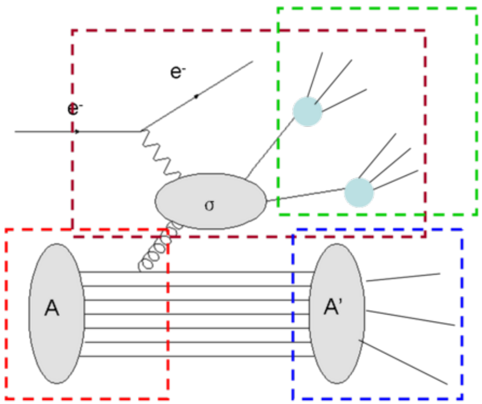
scaled 35% peripheral and 2.6% central



- Tagging allows us to select events for which the average d is very different from that for the entire nucleus

Jlab 2017-LDRD-6: Geometry tagging for heavy ions

- **Develop, test BeAGLE**
  - Focus on lower energy, forward charges detection
- **Applications:**
  - Color propagation in cold matter
    - Increase nuclear modificatons
  - Coherence and gluon saturation
    - Reach deeper in saturation regime



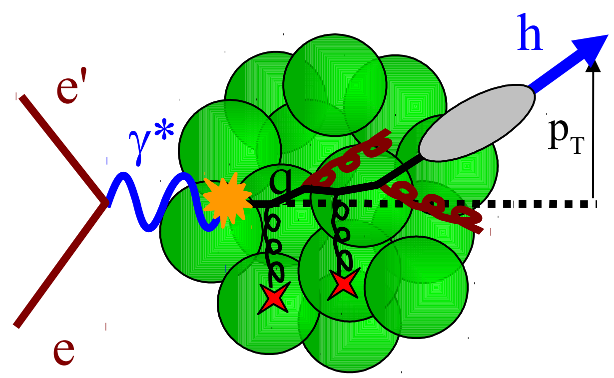
A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

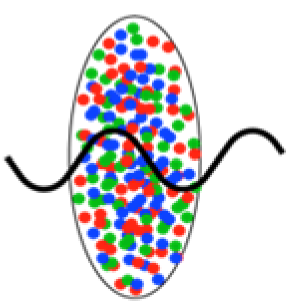
Nuclear geometry by DPMJet and nPDF provided by EPS09.

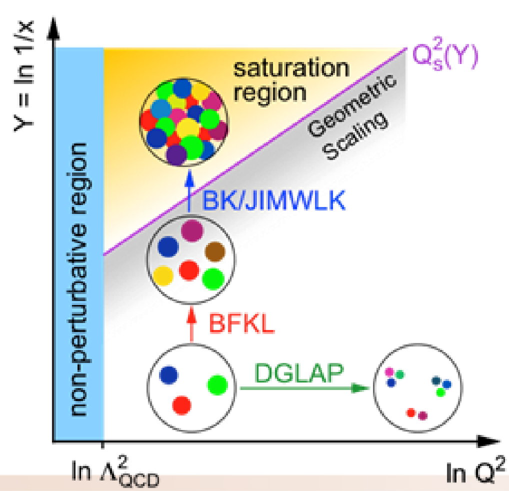
Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter







Summary

- **EIC has a unique "parton propagation and hadronization" program**
  - small to very large ν, high lumi SIDIS, heavy quarks, jets
- **Plenty to learn:**
  - soft gluons, energy loss, hadronization time scales
  - parton showers development
- **Deliverables:**
  - Characterization of cold nuclear medium
    - In terms of fundamental QCD correlators
  - Experimental benchmarking of models / calculations of
    - Hard probe propagation in cold nuclear matter
    - Parton shower algorithms

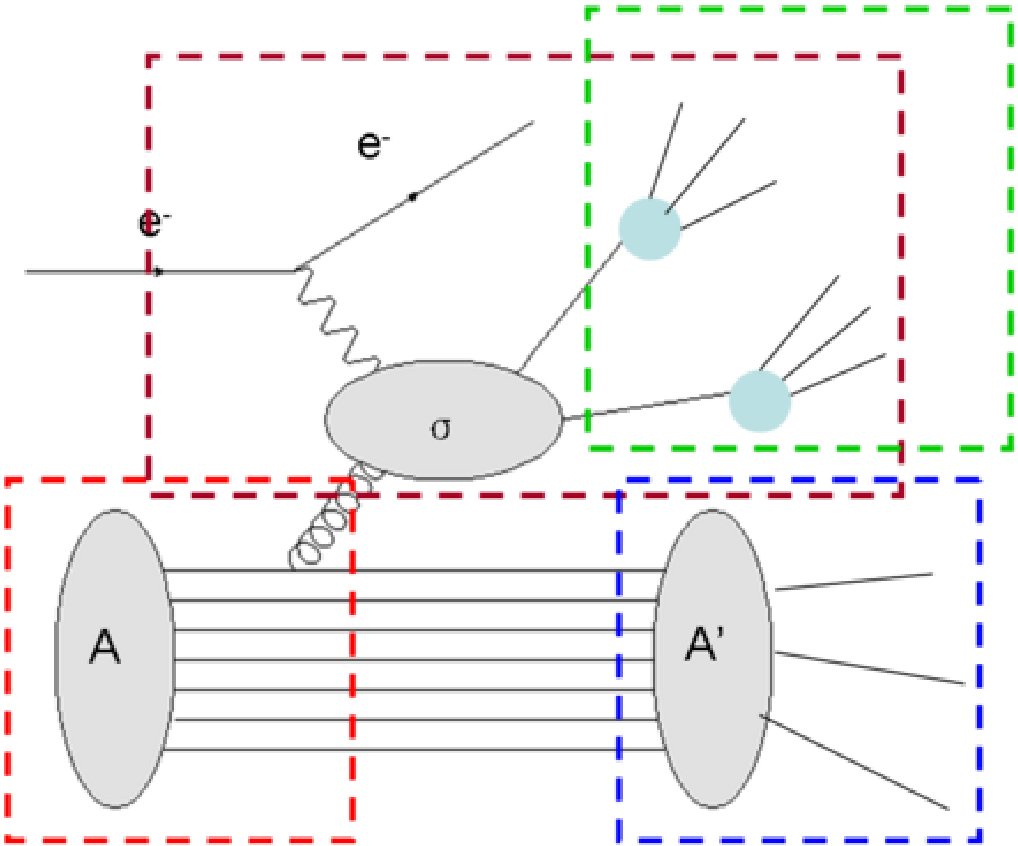
Go beyond "parameter hunting"
$\rightarrow$ understand in-medium QCD dynamics

Backup slides

BeAGLE (formerly, DpmjetHybrid)

Aschenauer, Baker, Lee, Zheng

- https://wiki.bnl.gov/eic/index.php/DpmjetHybrid



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